Modeling Blast Loading on Buried Reinforced Concrete Structures with Zapotec

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Overview

- Model response of a buried reinforced concrete structure to close-in detonation of a conventional explosive charge

- Many approaches exist for modeling blast/structure interaction
  - Engineering models, FE, Euler, ALE, CEL, FE/SPH, etc.
  - One-way coupling often used
    - Works well when the load duration is short compared to the response time of the structure
    - Problematic for long duration loading or complex structure geometries
  - Fully coupled analyses becoming more common

- Current work uses the coupled Euler-Lagrange (CEL) solution approach embedded within the Zapotec code
  - Investigate utility of CEL algorithm via benchmark calculations
  - Benchmarks derived from CONWEB test series

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What is Zapotec?

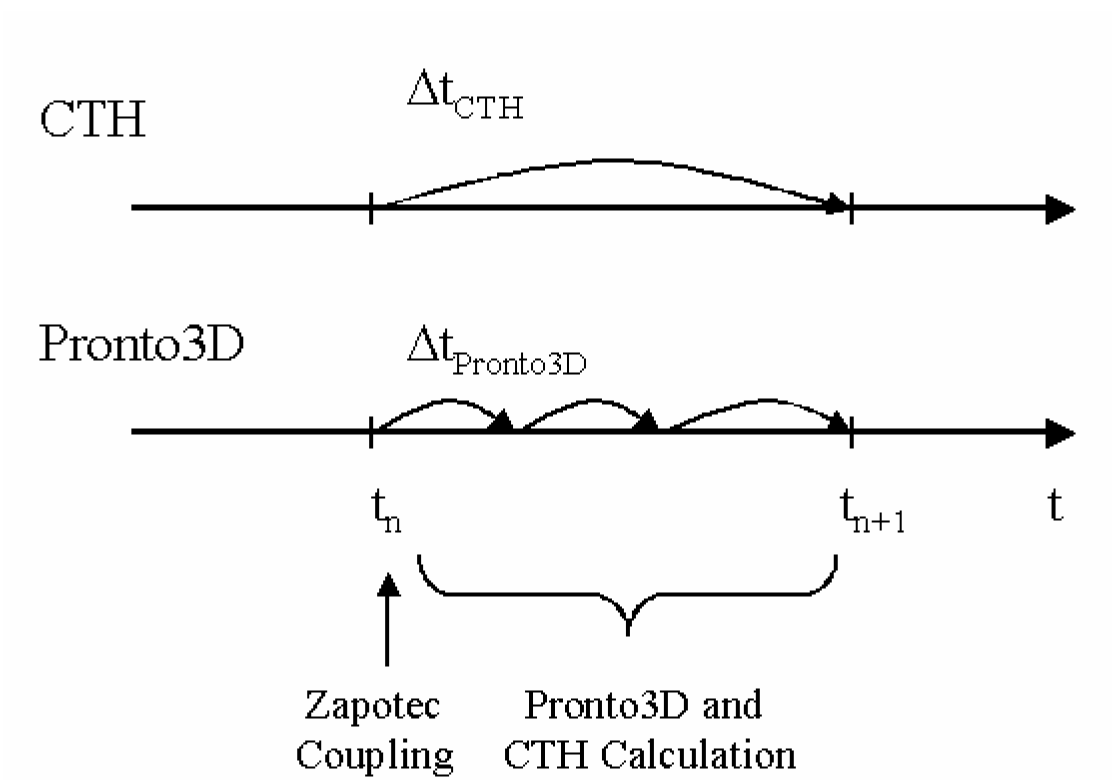
- Coupled Euler-Lagrange computer code

- Directly couples two production codes
  - CTH: Eulerian shock physics code
  - Pronto3D: Explicit, Lagrangian FE code

- Zapotec couples interaction between Lagrangian and Eulerian materials

Zapotec Background
The Coupled Algorithm in Time

- CTH and Pronto3D are run sequentially, cycle by cycle
- Algorithm permits Pronto3D subcycling



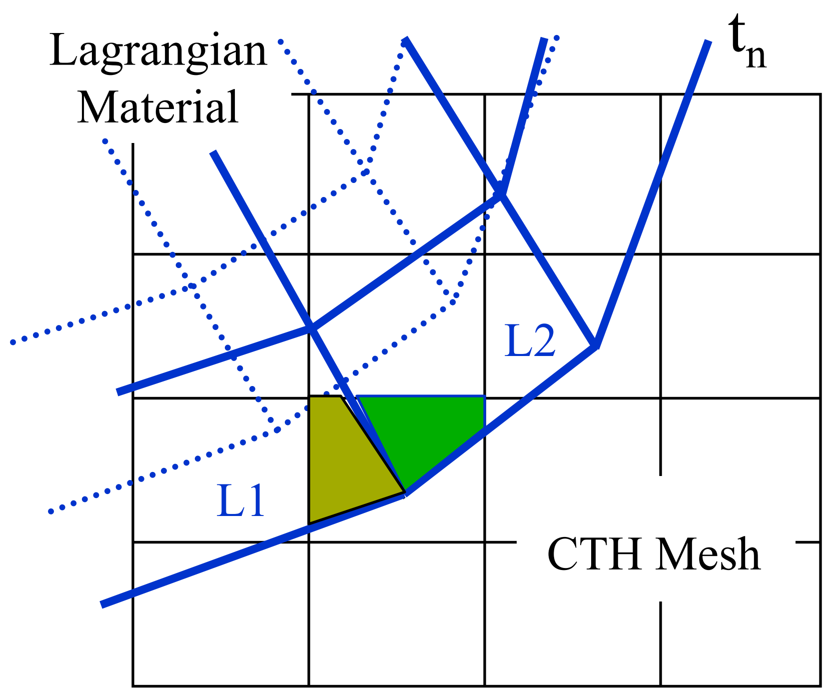
The Zapotec Coupling Algorithm

- Coupled treatment conducted in two steps, referred to as material insertion and force application
- Material insertion step updates CTH data
- Force application step updates Pronto3D data

The Zapotec Coupling Algorithm

Material Insertion Step

- Remove pre-existing Lagrangian material from the CTH mesh
- **Get updated Lagrangian data**
- **Insert Lagrangian material into CTH mesh**
  - Compute volume overlaps
  - Map Lagrangian data – mass, momentum, sound speed, stress, internal energy

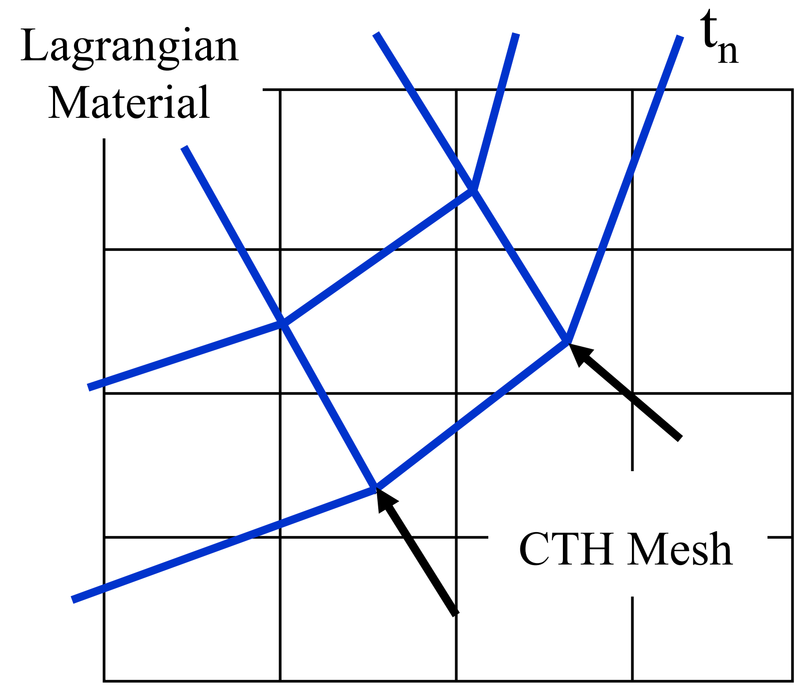


$$P_{L,inserted} = (V_{O,L1}\, P_{L1} + V_{O,L2}\, P_{L2}) / V_O$$

$$V_{overlap} = V_O = V_{O,L1} + V_{O,L2}$$

The Zapotec Coupling Algorithm
Force Application Step

- Remove pre-existing Lagrangian material from the CTH mesh
- Get updated Lagrangian data
- Insert Lagrangian material into CTH mesh
  - Compute volume overlaps
  - Map Lagrangian data
- **Compute external force on Lagrangian surface**
  - Determine surface overlaps
  - Compute surface tractions based on Eulerian stress state
  - Compute normal force on element surface (element-centered force)
  - If friction, compute tangential force as $\mathbf{f}_t = \mu f_n \mathbf{s}$
  - Distribute forces to nodes



$$\mathbf{f}_n = (\mathbf{t} \cdot \mathbf{n}_L)\, A_{overlap}\, \mathbf{n}_L$$

$$\mathbf{f}_I = N_I\, \mathbf{f}_n$$

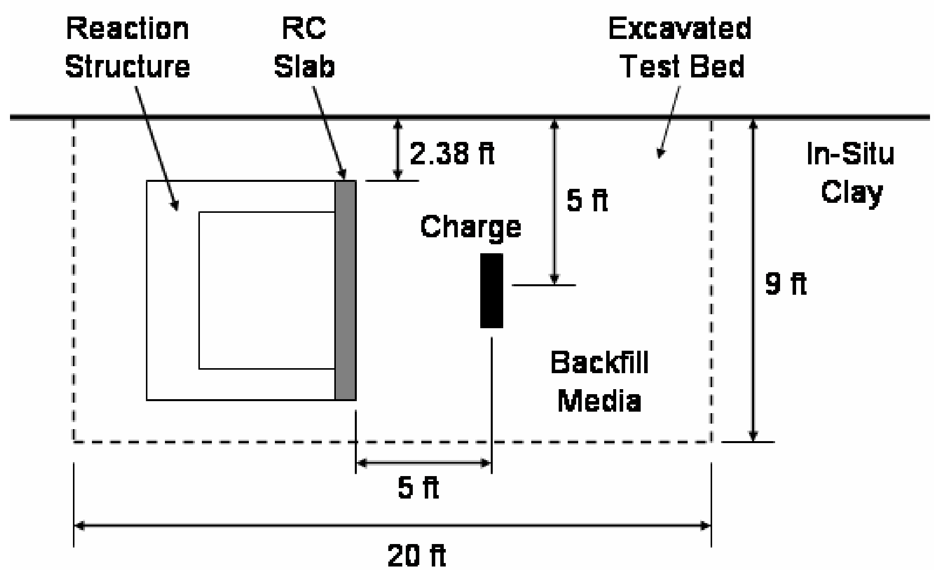
Benchmark Data

- Conventional Weapon Effects Backfill (CONWEB) Test Series
  - Conducted by Waterways Experiment Station in late 1980s
  - 15.4-lb cased C-4 Charge at 5 ft standoff
  - Controlled backfill: sand and clay
  - Test Structure
    - Reinforced concrete (RC) slab bolted to reusable reaction structure
    - Slab thickness varied (4.3 and 8.6 inches)
    - Reaction Structure: 15 ft long, 65 inches high, 4 ft deep
  - Structure and soil instrumented

- Test 1
  - Clay Backfill
  - Slab thickness: 4.3 inches

- Test 2
  - Clay Backfill
  - Slab thickness: 8.6 inches

- Test 3
  - Sand backfill in test bed
  - Neighboring material is in-situ clay
  - Slab thickness: 4.3 inches



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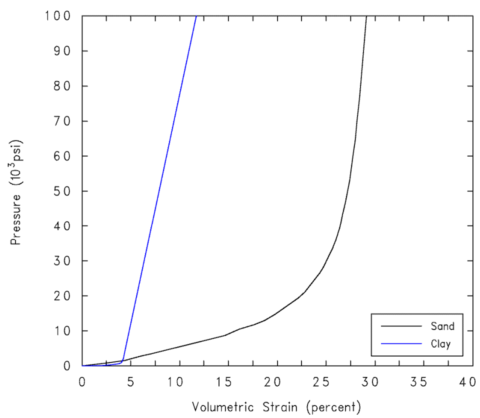
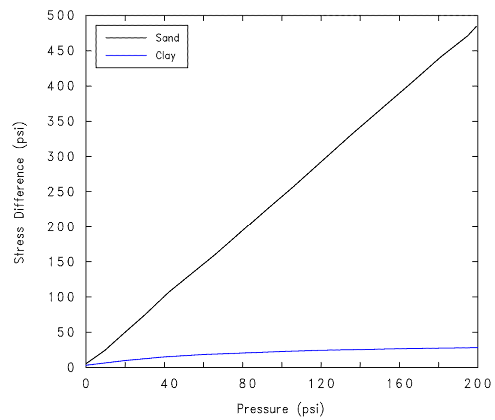
Analysis Overview

- Preliminary CTH analyses to develop material model for soil
  - Developed initial fit to hydrostatic and TXC data
  - Ran series of 2DC and 3D CTH standalone calculations to calibrate the model to better match measured free-field impulse and velocity data

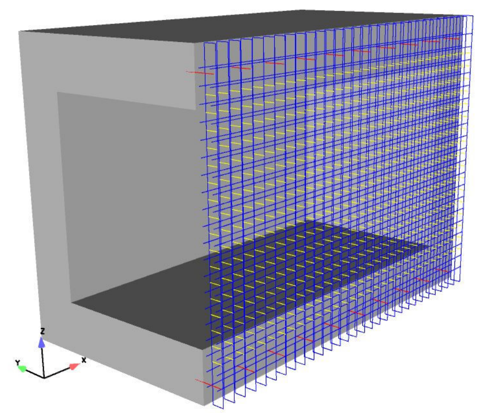




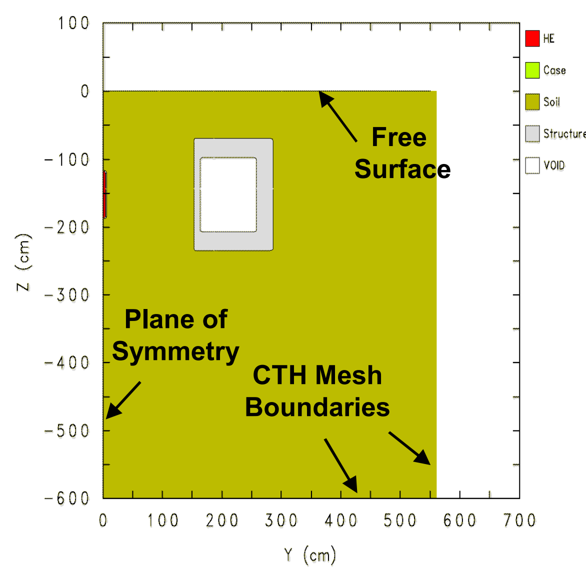
- Zapotec analysis
  - Soil and charge are Eulerian
  - Structure is Lagrangian
  - Comparisons
    - Interface impulse
    - Structure velocities
    - Slab permanent displacement
  - Many excursions calculations to assess modeling uncertainty

Problem Development

- Pronto3D
  - Detailed FE mesh of structure
    - Reinforcement and bolted connections explicitly modeled
    - Approx. 80K elements
    - Resolution ~ 0.75 inch (1.9 cm)
  - Material Modeling
    - Concrete: K&C Concrete Model
    - Reinforcement: Rebar Model



- CTH
  - Meshing
    - Mesh extended well beyond the structure
    - Approx. 1.7 million cells
    - Resolution ~ 1.2 inch (3 cm)
  - Material Modeling
    - Charge: JWL Library EOS for C-4
    - Steel Case: Elastic-Plastic material
    - Soil: P-alpha EOS with Geologic (GEO) strength model



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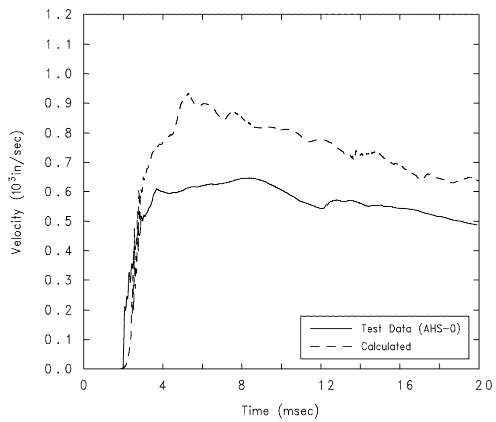
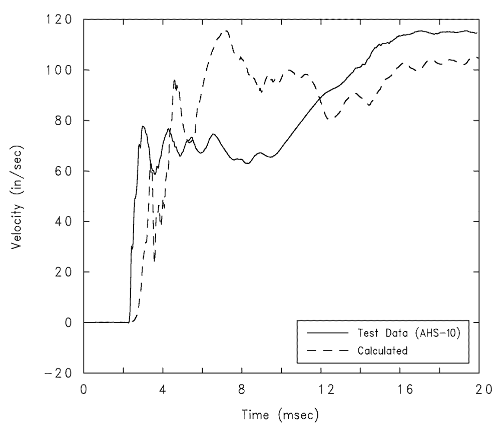
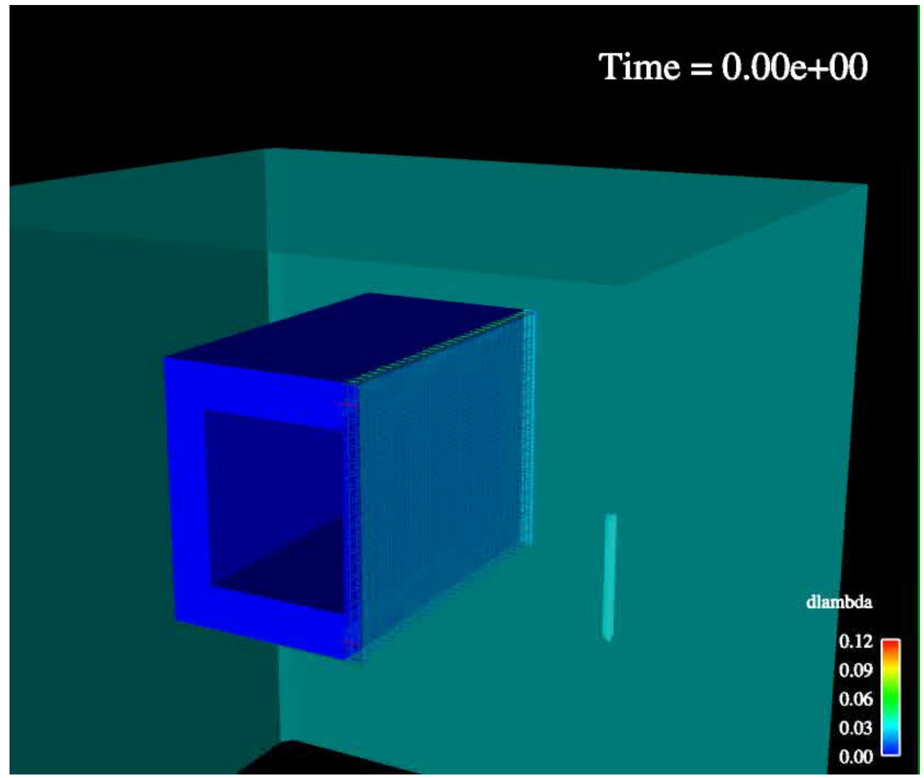
Typical Results
Test 1, Clay Backfill



AHS-0: Center of RC Slab



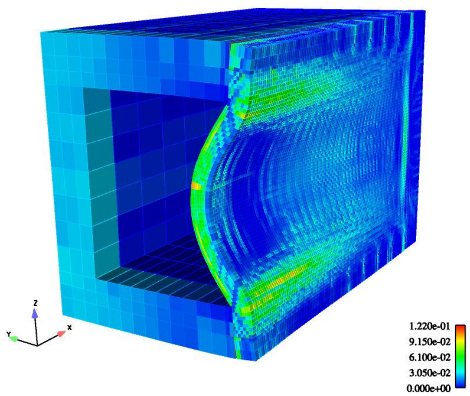
AHS-10: Base of Reaction Structure

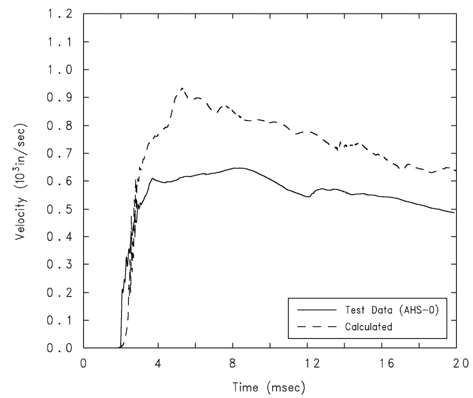


RC Slab:
- Thickness: 4.3 inches
- Strength (f_c'): 6095 psi
- Reinforcement: 1.0 %

Backfill: Clay

Influence of Slab Thickness



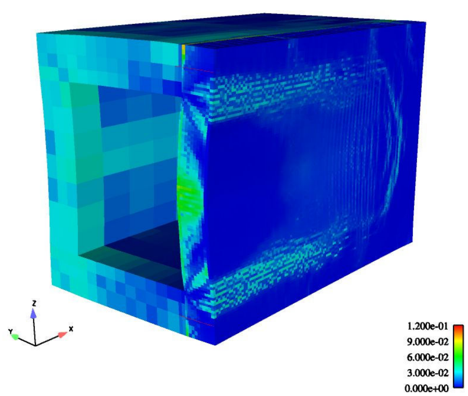


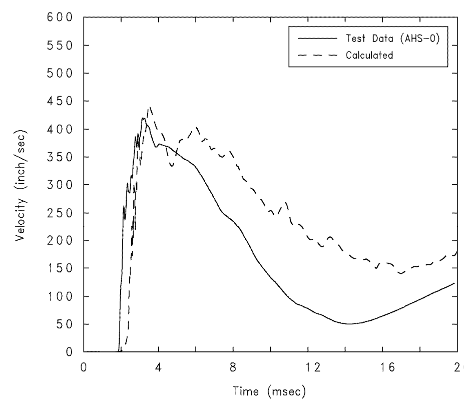
Structure Response

Measured: Breach (18 x 51-inch)

Calculated: Failed concrete at slab center and along supports

Test 1, T = 4.3 inches (p = 1%)





RC slab is not breached in test or calculation

Light-to-moderate damage to RC slab

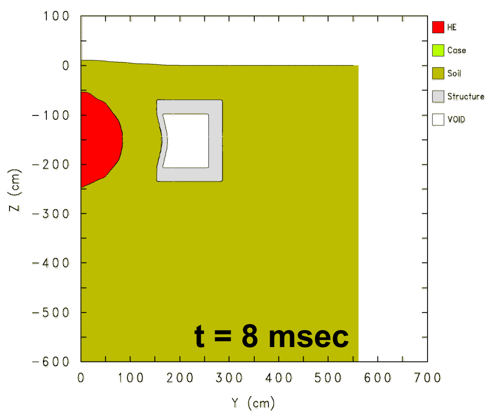
Permanent Displacement

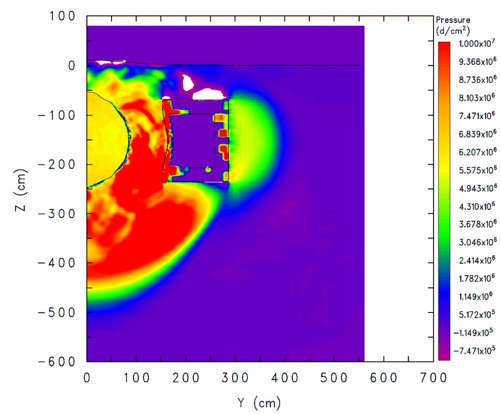
Measured: 1.2 inches

Calculated: 1.4 inches

Test 2, T = 8.6 inches (p = 0.5%)

Influence of Backfill Media



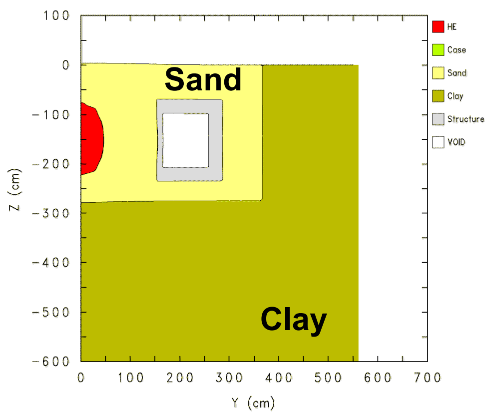


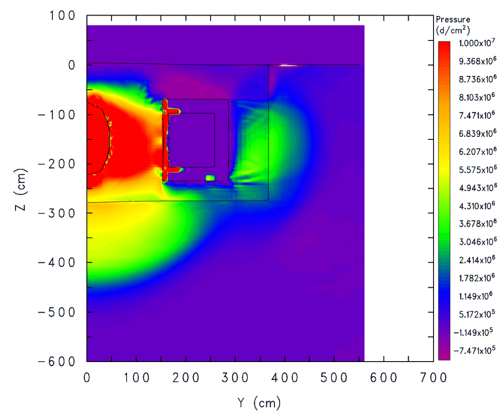
Test 1 – Clay Backfill

<u>Structure Response</u>

Measured: Breach (18 x 51-inch)

Calculated: Failed concrete at slab center and along supports





RC slab is not breached in test or calculation

Light damage to RC slab

Permanent Displacement

Measured: 1.1 inches

Calculated: 1.2 inches

Test 3 – Sand Backfill, In-situ Clay

Observations

- Coupled interaction arises from direct blast and rigid body motion of structure

- Fully coupled interaction over a long duration
  - Precludes use of one-way coupling
  - Most analyses run to 20 msec
  - Selected analyses run to 90 msec to recover permanent deflection

- Parameter study conducted to assess modeling uncertainties for Test 1
  - Assumed symmetry about charge
  - Treatment of bolted connections
  - Mesh resolution (CTH and Pronto3D)
  - Material modeling (rebar, concrete, and soil)
  - Variations in soil modeling had first-order effect on analysis

Observations (Cont'd)

- Modeling response of sand was problematic
  - Material model derived from static data, then calibrated to free-field data
  - Good comparison of peak free-field pressures, but significant under-prediction (~30 percent) of free-field impulse
  - TOA significantly under-predicted
  - Consequence: can expect under-prediction of loading on the structure

- Why was soil modeling an issue?
  - Recall, soil modeled using P-alpha EOS and Geologic (GEO) strength model
  - Material compaction cannot be recovered in P-alpha EOS
  - EOS and strength models operate independently
  - Porosity has no effect on yield

Concluding Remarks

- CEL approach shows promise for modeling the blast/structure interaction problem
  - Automatically handles interaction from direct blast and structure rigid body motion
  - Avoids complicated data handling associated with one-way coupling
  - Handles coupling over extended times

- Alternative constitutive model for porous, saturated soils is needed
  - New CTH model, Geo-Effective Stress, coming on-line

- Modeling structural damage/breach is an open issue